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Parallel Optical Random Access Memory (PORAM)

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PREFACE

This final report describes work performed at the David Sarnoff Research Center in the Optoelectronics Research Laboratory, M. Ettenberg, Director, under Purchase Order C-11854, issued by SRI International, Menlo Park, CA, Contract No. NAS 1-18226, Optical Recording Improvement for Space Station Data Management System. D. B. Carlin was the Project Supervisor, and G. A. Alphonse was the Project Scientist.

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EXECUTIVE SUMMARY

In this report, we show that the need to minimize component count, power, and size, and to maximize packing density require a parallel optical random access memory (PORAM) to be designed in a two-level hierarchy: a modular level and an interconnect level. A candidate for a suitable interconnect is described in detail in another report. Three designs are proposed in this report for the modules, in their order of R&D requirements. The first one uses state-of-the-art components, including individually addressable laser diode arrays, acoustic-optic deflectors and magneto-optic storage medium, aimed at moderate size, moderate power, and high packing density. The next design level replaces the magneto-optic medium with "electron trapping" (ET) medium to reduce optical power requirements. The third design uses a beam-steering grating surface emitter array to reduce size further and minimize the number of components. A prototype of the first design can be built as a tool for future study.

Section I

INTRODUCTION

The objective of this work is to investigate the viability of development of a parallel optical memory having no moving parts. While many high-performance optical data storage systems are currently being developed for eventual deployment on spaceborne platforms, all such systems rely on mechanical positioning of either the laser source or the storage medium, or usually, both. The elimination of moving parts has many advantages in spaceborne applications. Mechanical bearings introduce vibrations, both in the memory and the host spacecraft. Air bearings, often used in high-performance, ground-based applications, are not suitable in space. Mechanical components are subject to wear and eventual failure; their relatively low cost is mitigated by this consideration in space. In addition, the angular momentum of systems composed of an odd number of rotating optical disks will be transferred to the host spacecraft, necessitating corrective action in order to preserve angular orientation of the vehicle.

An optical memory application of interest for spaceborne deployment is one involving parallel processing in which several processors are required to address individual, dedicated modules that are parts of a larger optical memory. For example, the computer system may be based on a set of IBM 1750A processor chips. This processor has a 32-bit word, a clock rate of 20 MHz, and can be configured to address a memory field of 10^6 bits (actually 32,768 words of 32-bit length). The optical memory system would then consist of an array of 10^6 bit modules that may be assigned to the processors either on a one-to-one basis, a one-to-many basis, or a many-to-many basis in some form of matrix.

A completely parallel optical random access memory, one in which any bit is randomly and directly accessible, would have a very low packing density and would consume considerable electrical power. The use of deflectors would reduce power consumption if it does not significantly reduce the packing density much below what is attainable in rotating disk systems. An example of a low packing density memory without moving parts is a block-oriented system described in the Appendix. This type of memory, which we contemplated at the beginning of this study, has a packing density that is only 6% to 7% of that of a rotating disk system.

Currently available non-mechanical deflectors, such as acousto-optic devices (AO), have small deflection angles and require beam expanders and other optical components to resolve a large number of spots. However, there are many new optical devices that can be used to make a novel storage system. Grating surface emitter (GSE) laser diode arrays can be designed to have beam-steering capability with angular range comparable to or larger than AO deflectors and may eventually supplant the latter for some applications. Individually addressable linear array of diodes can be used to simultaneously address several memory locations. Several media now exist that have interesting properties for optical data recording. Although some of those components are still in the R&D phase, they allow us to explore anew the feasibility of an optical random access memory without moving parts.

In this report, we start by exploring how parallel operation effects power, component count, and packing density. We show that the simplest form of parallel memory is not practical. We also show that the use of deflection systems is necessary to achieve a reasonable packing density and reduce power consumption. Starting from a concept that uses several memory modules*, we interconnect them to processors in a way similar to a design developed in a concurrent study by J. H. Hammer at the David Sarnoff Research Center and described in a report, entitled "Optical Backplane Interconnect Technology (OBIT)" [1]. We then proceed to develop designs for the modules, taking into account the need to minimize power and component count, and maximize packing density. We propose three designs, in their order of R&D requirements. The first one uses state-of-the-art components, including individually addressable laser diode arrays, AO deflectors, and magneto-optic (MO) storage medium, aimed at moderate size, moderate power and high packing density. The next design level replaces the MO medium with the electron trapping (ET) medium to reduce optical power requirements. The third design uses a beam-steering grating surface emitter (GSE) array to reduce size further and minimize number of components.

* H. Hendricks, NASA, Langley, private discussion.

Section II

SYSTEMS DESIGN CONSIDERATIONS FOR A PARALLEL OPTICAL RANDOM ACCESS MEMORY (PORAM) WITHOUT MOVING PARTS

A totally parallel optical random access memory (PORAM) with no moving parts is the single-level system shown in Fig. II-1. It consists of a storage medium with an array of writing and readout modules for each bit, all of them being independently addressable. The write modules consist of a laser source and accompanying collimating and focusing optics. The readout modules consist of a collector lens and a photodetector. Not shown are the drive electronics, sense amplifiers, and bias coil (if the storage medium is a magneto-optic material). This system illustrates the advantages of a parallel system, but also it points out the difficulties in achieving practical designs.

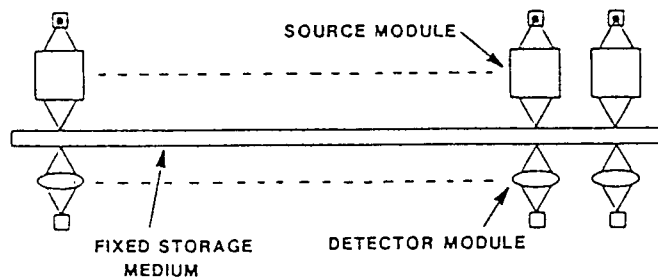


Figure II-1. Simplified concept of a PORAM without moving parts.

Several factors must be taken into consideration in the design of a PORAM for spaceborne applications. They include: fast access time, high packing density, low power consumption, low component count, high speed, small weight, and compactness.

The only advantage offered by a system such as that shown in Fig. II-1, a PORAM in the true sense, is the short access time. The access time is limited only by the switching electronics and the turn-on time of the laser modules. There is no latency time, as encountered in mechanical systems involving

rotating media. The data rate is also high, being determined mainly by the writing time.

Such a memory system is, however, not practical, especially for spaceborne applications, because it suffers from excessive power consumption, excessive component count, and extremely low packing density. The excessive power consumption and component count result from the fact that a separate source, power supply, detector is required to operate each memory bit. For an MO memory, each laser must deliver about 30 mW of power, and this translates to at least 60 kW of electrical power for a 10^6 bit module with 50% laser efficiency. In addition, component count is very high since the module would require 10^6 sources and 10^6 detectors with their respective optical components. As for the packing density, it is clearly limited to one bit over the area covered by the optics of the write module. If the diameter of the recording lens is D in mm, the packing density is simply $4/\pi D^2$ bits/mm². Those points are being emphasized here because they represent unavoidable drawbacks in any PORAM in the true sense of the word.

Those drawbacks just discussed clearly indicate that a completely parallel large-capacity optical data storage of the type shown in Fig. II-1 is not only undesirable for spaceborne applications but also impractical. Some degree of serial addressing is thus desired in order to reduce power and component count and make better use of storage medium capacity. As will be seen below, the effect of complete parallelism can still be achieved by simply interposing a switching network between processors and modules.

For the purpose of this study, we will conceptualize the storage system as an array of 10^6 bit modules addressed by an array of 1750-A processors. The modules will consist of 32,768 words with 32 bits/word. The 32 bits/word are selected (in parallel) at least for writing. The words at any memory address are randomly accessible by means of optical deflectors, but they are not simultaneously addressable. We propose to link the modules to the processors via an interconnecting network as shown in Fig. II-2. This network can be electrical or optical. Thus, the proposed PORAM is a two-level system consisting of a modular level and an interconnect level.

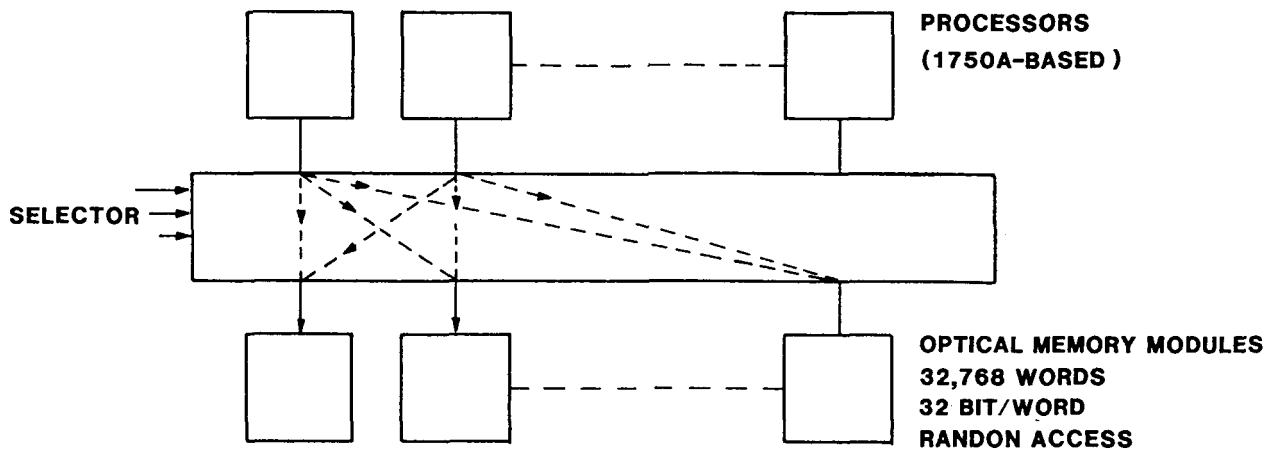


Figure II-2. Two-level concept of a PORAM without moving parts.

The use of an optical interconnect is attractive because of its inherent speed and lack of clutter. This subject is undergoing intensive research at the present time, as witnessed by the several conferences where it is discussed. An interesting optical interconnect for this application is described and analyzed in the "OBIT" report described in the preceeding section. The interconnect can be configured such that either a single module is dedicated to a single processor, or such that any processor can address any module, as shown by the dashed lines in Fig. II-2, and in this manner, any processor can have random access to any word in any module. Therefore, the two-level system in Fig. II-2 does fulfill the requirements of a true PORAM just as well as the single-level concept of Fig. II-1. Our remaining tasks will be to conceive practical designs for the modules, within the constraints of high packing density, random accessibility, acceptable power consumption, and compactness.

Section III

SUBSYSTEM OR MODULE DESIGN

The advent of individually addressable linear laser diode arrays [2] and erasable media [3,4], and the emergence of surface emitters [5,6], and beam-steerable surface emitter arrays [7] of visible lasers and of high-sensitivity storage media (such as electron trapping materials) [8] have made it possible to conceive acceptable and even attractive designs of optical data storage modules without moving parts, without excessive space occupancy, and without sacrifice of packing density. We present here three designs, in a hierarchy of increasing levels of sophistication and ascending order of R&D requirements. The first design involves the use of state-of-the-art semiconductor laser diode arrays, acousto-optic deflectors, and currently available erasable media. The next design is one that uses two wavelengths and a new electron trapping or ET erasable medium whose optical power requirement is two orders of magnitudes lower than current media. The third design is still a more compact one that uses a steerable grating surface emitter array that combines in one unit both the source and deflector functions.

A. DESIGN #1 - USE OF STATE-OF-THE-ART COMPONENTS

Our first-level design of an optical memory module without moving parts is shown in Figure III-1. It is a word-addressable 10^6 bit memory (in this report, it is understood that a 10^6 bit memory implies a 32,768 word memory having 32 bits/word) and corresponds to one of the modules in the system illustrated in Fig. II-2.

The module consists of a 32-element individually addressable monolithic array of laser diodes acting both as a source and as a word composer, an anamorphic beam expander to reduce beam divergence and satisfy the AO deflector's aperture requirements, two 1024 position AO deflectors (one for horizontal, one for vertical deflection), and recording lens and an erasable recording medium. The system is designed to read out by reflection, so the storage medium is deposited on a substrate of suitable shape to reflect the readout light through the recording lens and deflectors so it can be focused onto the detector array.

For a single lens to be used in the optical train, it is necessary for the individual elements of the laser diode array to have a slight angular separation. If the angular range of the AO deflectors is assumed to be 100 milliradians, with expanded beam diameter 1 cm, wavelength 0.8 μm , and deflector resolution 1024 positions, this angular separation is about 0.1 milliradian, and it can be incorporated in the geometry of the masks used to fabricate the array. Data is stored as 32 words horizontally and 1024 words vertically, and the memory is addressed by the application of a frequency increment Δf to the Y deflector piezoelectric transducer and $32\Delta f$ (32 spot locations per word) to the X deflector transducer. Hence, both deflectors have the same resolution of 1024 positions. Such high-resolution deflectors are commercially available. They typically use a GaAs AO medium and have an optical efficiency of about 32%. The storage medium can be any state-of-the-art erasable medium. In Fig. III-1, we show an MO medium of size 2 mm x 2 mm with a coil around it for magnetic bias. It should be noted that the packing density in this memory is the same as for rotating disk media and it is determined strictly by the diffraction limits of the optics. However, since the storage medium is the smallest component in the whole module, some leeway is allowed in its size to minimize cross-talk. For example, if the numerical aperture of the recording lens is 0.5 and the laser wavelength λ , the required linear dimension of a bit is about 2λ , and the linear dimension of the storage medium is 2000λ or 1.6 mm for 0.8- μm wavelength. Thus, the choice of 2 mm is quite adequate.

The operation of the module is straightforward. For writing, a memory address is selected by the application of suitable frequencies to the deflector transducers, and the word to be written is composed by energizing the appropriate array element. To read out at a particular location, a lower current is applied to all the diode elements, while the deflectors and detector array are activated. Erasing is done similarly, but with the same laser power as for writing and without activating the detectors.

The unit is fairly compact, about 20 cm long, and the storage medium packing density is comparable to rotating disk. Due to the relatively low AO efficiency (32%), the overall optical efficiency is less than 10% for recording and 1% for readout on reflection. This is not a problem for reading out phase-change erasable media, but it could affect the performance of MO media. At any rate, the laser power should be 60 to 80 mW for writing and 30 mW for reading MO (3 mW at the medium). The memory random access time is about 1 μs , the time required

by the acoustic wave to traverse the deflectors optical aperture. It should be noted that although the storage area is smaller than a chip of comparable capacity, the overall optical package is larger, slower, and consumes more power. On the other hand, if the storage medium were allowed to move, this module would make a very interesting attractive optical tape recorder.

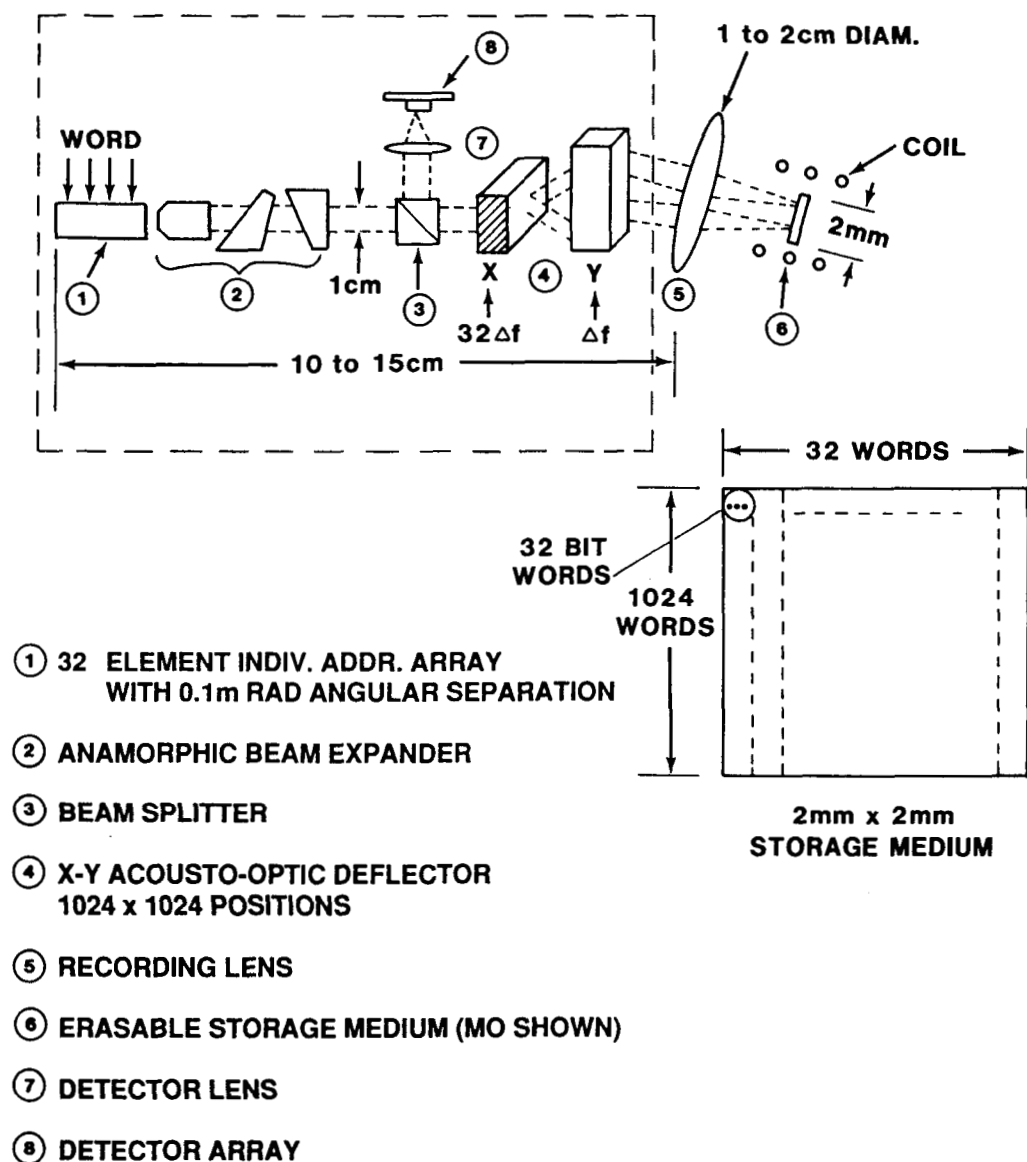


Figure III-1. Design of optical memory module without moving parts using state-of-the-art components.

B. DESIGN #2 - REDUCING OPTICAL POWER USING ELECTRON TRAPPING (ET) STORAGE MEDIUM

The requirement of 60 to 80 mW/element in the laser diode array discussed in Design #1, while not unreasonable, represents a reliability issue. Not enough data is available on those arrays at such power levels. Less light is desirable for both writing and reading, implying that a more sensitive storage medium is desirable. Several new media and recording processes are currently under study. They include the modification of surface states in some media, the synthesis of DNA-type molecules in others [9], and the use of electron traps (ET) in some types of phosphor. The ET material is very promising as an erasable storage medium because of its high sensitivity, reversibility, and potential ease of fabrication. The basic material is a high-bandgap (about 3 eV) II-VI compound doped with rare-earth elements to create energy states within the material's bandgap. Those states are stable at room temperature as long as their density is low enough to prevent overlap wavefunction. Light at the bandgap wavelength (450-nm blue light) excites electrons that are then trapped by the impurity levels within the bandgap. These electrons can then be excited out of the traps by an infrared light at wavelength of 800 to 900 nm, and upon such excitation, they return to their ground state, emitting a yellow light of wavelength about 550 nm. There are about 10^8 traps/cubic microns in the material, so it takes about 10^8 blue photons/cubic micron to saturate the material during writing (assuming 100% quantum efficiency). The significance of this number is that it represents about 10^{-11} J of blue light to saturate the material while writing a 1- μ m bit. By comparison, MO and phase-change media require at least 5×10^{-10} J for writing and, therefore, the ET material's writing sensitivity is more than 50 times better than MO and phase-change media. Hence, the laser light output needs to be only about 1 mW for high-speed writing (100 ns), or about 0.1 mW for writing in 1 μ s (the access time of AO deflectors). The reading sensitivity is even more attractive. The developers of the material claims that it takes 10^{-15} J at 900 nm to readout with a signal-to-noise ratio of over 20 dB. This corresponds to about 10^4 readings before a refresh. Complete erasing would require about 10^{-11} J. A memory system using this material would thus require less than 1 mW/bit from a blue-light laser for writing, even less power at about 900 nm for reading, with the detectors optimized (by means of filters) to respond to the yellow 500-nm output light.

We propose a memory module based on ET storage medium as our Design #2, and it is shown schematically in Fig. III-2. It uses two individually

addressable arrays, a blue light (450 nm) for writing and an 850 to 900 nm light for reading. Their layout is similar to the one used in Design #1. The dichroic prism is used to give both sources usage of the same optical path. The 450-nm sources can be obtained either as blue lasers or as frequency-doubled light from a 900-nm source. The frequency doubling scheme is acceptable because the required light output at blue wavelength is not high. The same X-Y deflectors are used for both wavelengths, but a different set of frequencies is used for each. The frequency synthesizer design can be simplified by choosing the wavelengths to be 450 nm and 900 nm, i.e, specifically in a ratio of 2. Since the AO deflection angle is proportional to the optical wavelength and the acoustic frequency, then if Δf steps are used for reading at a given location, $2\Delta f$ steps will be used for writing at that same location.

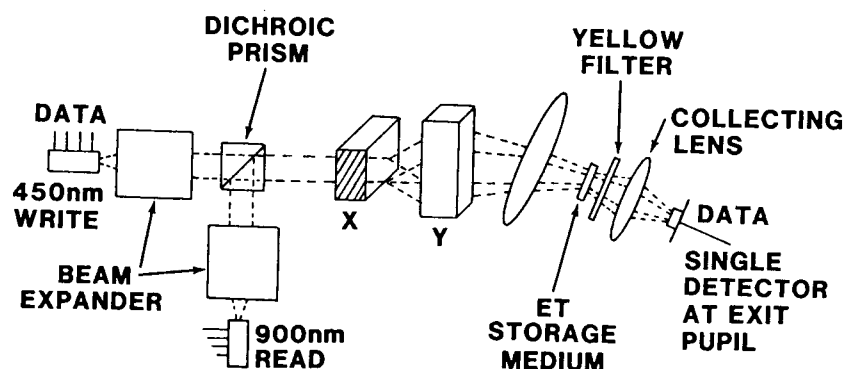


Figure III-2. Optical storage module using electron-trapping medium.

The data output is a broad spectrum light centered at about 550 nm emitted at the data points. It is important to be able to use a *single* detector or a set of detectors at a *fixed* location for *all* the addresses, in order to avoid the need for one detector for each data location. The simplest approach is to use a collecting lens one focal distance away from the storage medium and one single detector at its exit pupil as shown in Fig. III-2. The output data can be visualized as point sources of yellow light emitted at the locations on the storage medium selected by the 900-nm light. The latter light is blocked by the yellow filter and, since the light from any location passes through the exit pupil (the conjugate focal length) of the collecting lens, a single detector can be placed at that plane to collect the data,

with the condition that *only one bit be read at a time*. This statement implies that in order to use this simplified readout scheme, the elements of the 900-nm readout array source must be selected serially. This is not a problem, due to the AO deflectors relatively slow speed. Thus, since the AO speed is about 1 μ s, systems operation will be transparent to the serial readout rate of the latter, which is about 30 ns/bit.

C. DESIGN #3 - SIZE REDUCTION AND SPEED IMPROVEMENT BY MEANS OF BEAM-STEERING MULTIELEMENT ARRAYS

1. Beam-Steering of Grating Surface Emitters

In the two designs discussed so far, most of the space needed for the module is occupied by the optical train consisting of the sources, beam expanders, and deflectors, as illustrated by the dashed rectangle in Fig. III-1. Furthermore, the speed is limited by the AO transit time. It would be desirable to combine them into one single element. In due course of time, this should become possible with beam-steering grating surface emitter arrays.

The diode arrays discussed in the two preceeding designs are likely to be edge emitters of the types used for multichannel optical disk recording. However, there is a growing body of researchers actively developing grating surface emitters (GSE) [5] for applications such as high-power, low beam divergence coherent sources for space communication, optical interconnect, optical printing, etc. The David Sarnoff Research Center (Sarnoff) has accumulated extensive experience and capability in one-dimensional and two-dimensional GSE arrays, including beam-steering. A simple GSE semiconductor laser is a structure that consists of a gain section to provide optical amplification and a waveguide section with a grating to provide feedback and output coupling as shown in simplified form in Fig. III-3.

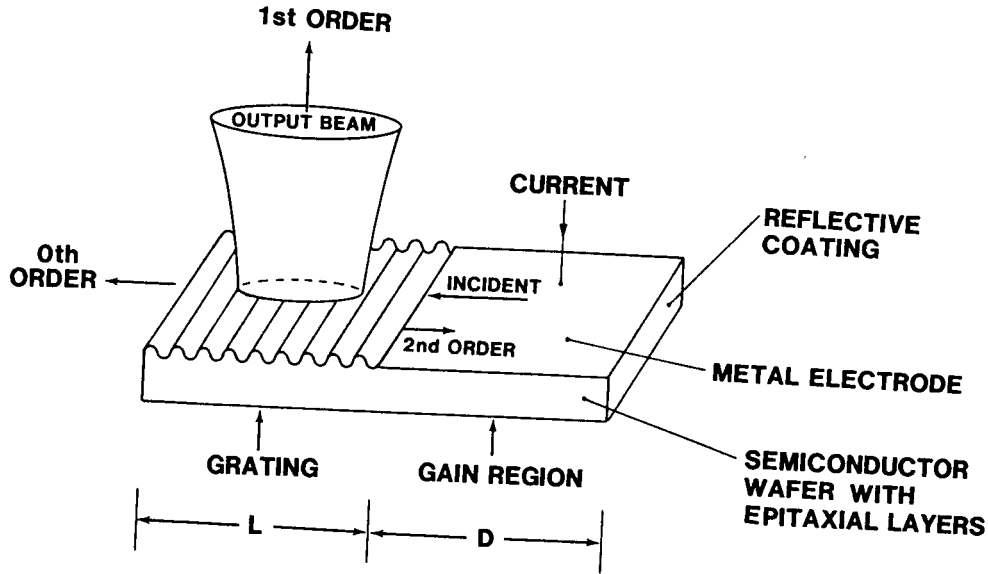


Figure III-3. Grating surface emitter semiconductor laser diode.

The grating is designed with a diffraction angle of 90° between propagating orders, and with only the first and second orders being significant. Thus, light incident on the grating from the gain region will have its first-order diffracted light emitted perpendicular to the grating surface, with the second-order light fed back into the gain region. The lasing feedback is provided by this second-order light from the grating on one side of the gain region and by facet reflection from the cleaved side. The first-order light from the grating is used as the laser output. The output angle from a Bragg grating of period d fabricated in the waveguide of a laser is given by [10]:

$$\sin\theta = \frac{\lambda_0}{d} - n_e$$

where λ_0 is the wavelength of the light in free space, and n_e is the effective refractive index of the waveguide mode. By varying λ_0 , d , or n_e , the output can be made to vary.

The grating spacing d cannot be changed readily, but there are several ways to change λ_0 and n_e . The gain region can be considered as a Fabry-Perot cavity of length D , and the wavelength is given by

$$\frac{m\lambda_0}{2n_g} = D$$

where n_g is the effective index of the gain region and m an integer. Now it is well known that n_g is affected by the laser pump current and temperature. The latter can be controlled by means of a thermoelectric unit, but the response time is much too long to be recommended. Changing the current is, however, an acceptable way to change the wavelength and, hence, the output angle, but it also affects the gain, hence the output intensity. The best approach is to add a phase modulator section [11] in the structure, as shown in Fig. III-4, to control the wavelength through the refractive index, so the output power can be controlled independently.

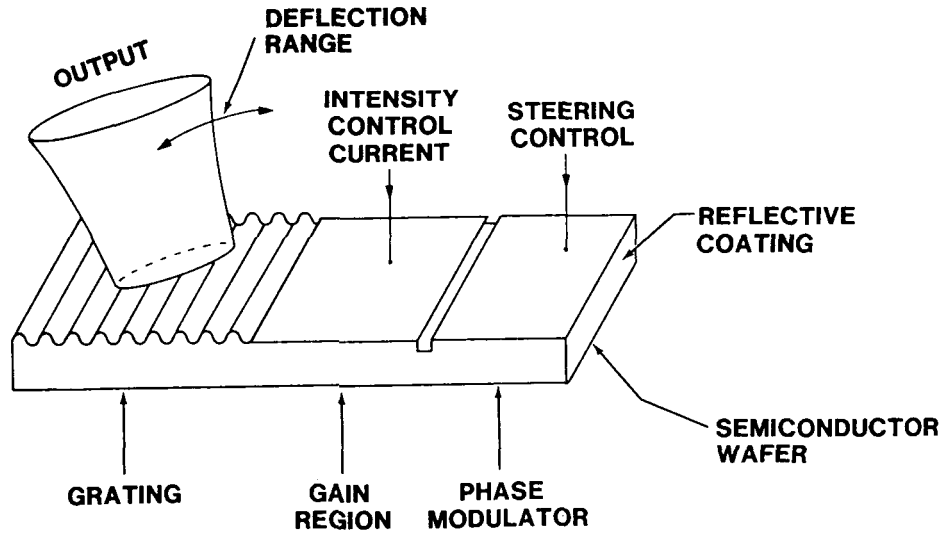


Figure III-4. Grating surface emitter with phase modulator for beam-steering.

The resolution or number of resolvable spots N is the ratio of the obtainable angle range $\Delta\theta$ to the diffraction spread $\delta\theta$ of the light from the grating. It is also equal to the ratio of the total wavelength change $\Delta\lambda$ to the change $\delta\lambda$ required to move the beam through an angle equal to the full-width-half-maximum divergence in the far field. Thus

$$N = \frac{\Delta\theta}{\delta\theta} = \frac{\Delta\lambda}{\delta\lambda}$$

This formula can be used to estimate the required grating length for 1000 spot resolution. For GSE's, measured values $\Delta\theta$ and $\Delta\lambda$ are 4° (70 milliradians) and 160 Å, respectively. Also, $\delta\lambda$ in Å is approximately given by $1600/L$, where L is the grating length in micron, and from diffraction theory $\delta\theta \approx \lambda/L$. From this information, one deduces that the number of resolvable spots is proportional to the grating length, and that, with the current designs, the latter must be of the order of 12 mm. This length does not represent a problem if the grating is lossless. With AlGaAs GSE's, the grating length can be kept to about 1 mm to minimize losses, so additional gain is required for a total grating length of 12 mm. This can be obtained by making a linear array of alternating gain and grating regions in a linear array, as shown in Fig. III-5. Only four gain sections are shown, but the total number may have to be 10 to 12. The sections are injection-coupled by means of the residual zero-order light that has propagated through the grating (Fig. III-3), and, therefore, they all emit in a single wavelength. One such linear array would be used for each bit of a 32-bit word, and the beam would be steerable by means of the current applied to the phase modulator. Such a linear array of surface emitters, without the phase modulator, has been fabricated at Sarnoff.

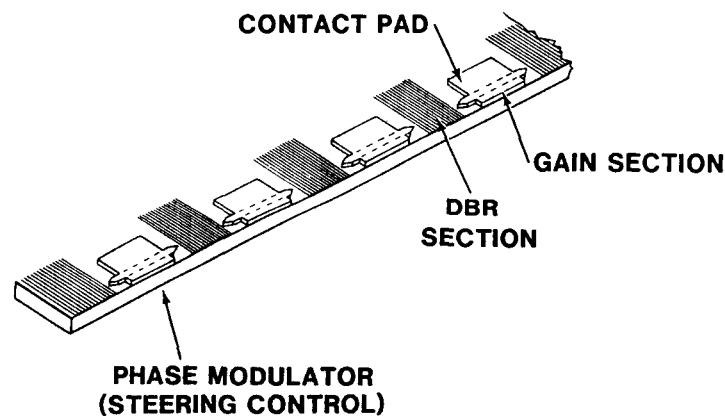


Figure III-5. Beam-steering linear array of grating surface emitters.

The complete source-deflector array for 32 bits would be a monolithic chip containing 32 such linear beam-steering arrays designed to be independently addressable, although in principle sharing a common phase modulator. A simplified sketch of this chip is shown in Fig. III-6. The injection locking is obtained by designing the grating such that a small fraction of the zero-order light

from one element is able to propagate across the grating to be amplified by the next gain element.

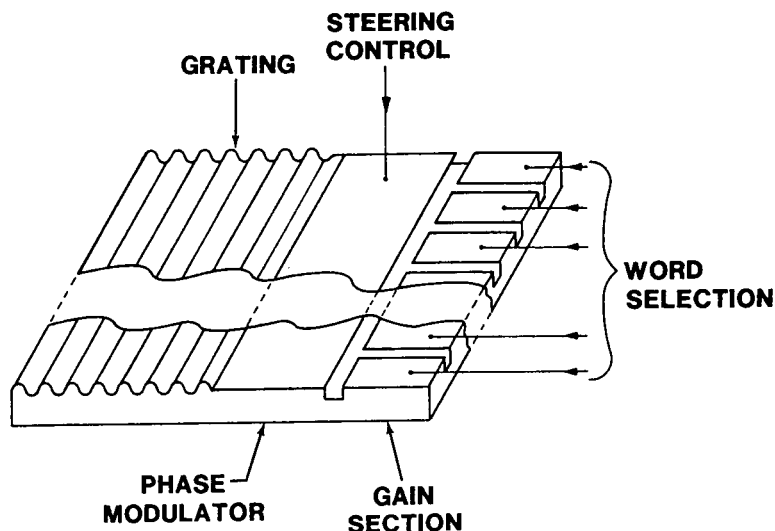


Fig. III-6. Monolithic array of beam-steering surface emitters.

2. Optical Memory Design Using Grating Surface Emitters as Deflectors

Our third design is shown in skeletal form in Fig. III-7. It uses a beam-steering GSE such as shown in Fig. III-6 to replace the source, beam expander, and one of the deflectors, thus making the optical train quite compact. In the due course of time, two-dimensional beam-steering can be contemplated, but we are proposing one-dimensional steering for the moment. The sketch in Fig. III-7 is shown with an MO storage medium, but it is readily extendable to include other media such as the ET medium suggested in Design #2.

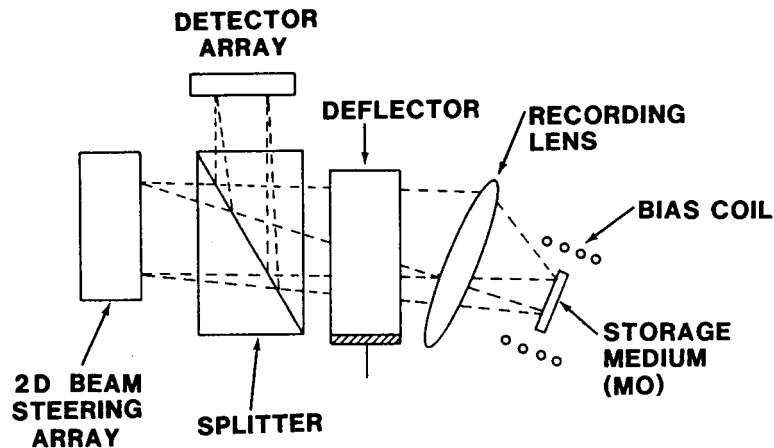


Figure III-7. Compact optical memory module using grating surface emitters as sources and deflectors.

The implementation of this design requires the development of the GSE array shown in Fig. III-6. The technology involved in its development is the same as that for the current two-dimensional GSE arrays currently under development at Sarnoff. Our proposed structure for parallel optical recording is actually simpler because there is no need for the evanescent or the Y guide coupling required for the two-dimensional array. The beams are uncoupled; their gain sections are individually addressable, but the phase controller and grating are common to all of them. Such an array is worth developing, and it would find applications in several other areas.

Section IV

CONCLUSIONS AND RECOMMENDATIONS

In this study, we have shown that the need to minimize component count, power and size, and the need to maximize packing density require a parallel optical random access memory to be constructed in two levels. One level consists of a set of moderate-capacity random access modules, and the other level is an electrical or optical interconnect that permits a set of processors to randomly access the individual modules. In this manner, any of a number of processors can have random access to any word in any module. Any other processor can have access to any of the remaining free modules during that time. This hierarchical approach allows dependent design, high-performance interconnects and modules. An example of the interconnect is discussed in an accompanying report "Optical Backplane Interconnect Technology (OBIT)" by J. M. Hammer of the David Sarnoff Research Center.

The study reported here has focussed on the design of the individual memory modules with the specification that they contain no moving parts. We have proposed three designs, in their order of increasing R&D requirements. The first design uses state-of-the-art components, including individually addressable laser diode arrays, AO deflectors and magneto-optic storage medium, aimed at moderate size, moderate power, and high packing density. The next design level replaces the MO medium with an electron trapping (ET) medium to reduce optical power requirements. The third design uses a beam-steering grating surface emitter (GSE) array to reduce size further and minimize the number of components.

The first design can be implemented in a relatively short time, using state-of-the-art components, and it can be used to prototype the concept of a compact PORAM having no moving parts. The ET material that promises to reduce power consumption is currently in the development stage and will probably be available in about three years. The beam-steering array may require a similar development time, but it may require some technological breakthrough to get the desired capacity. Such breakthroughs would involve means of increasing the angular range or the wavelength shift, perhaps to beyond 1000 Å. This report can serve as a guide toward further analysis, prototyping, and development work.

Section V

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Appendix A

HISTORICAL BACKGROUND OF OPTICAL MEMORIES WITHOUT MOVING PARTS

A. HOLOGRAPHIC PAGE-ORIENTED MEMORY

There was a flurry of activities in the early 70's in holographic data storage [12,13]. Several configurations were designed, all of them having no moving parts. A typical holographic read-write optical data storage is shown in Fig. A-1.

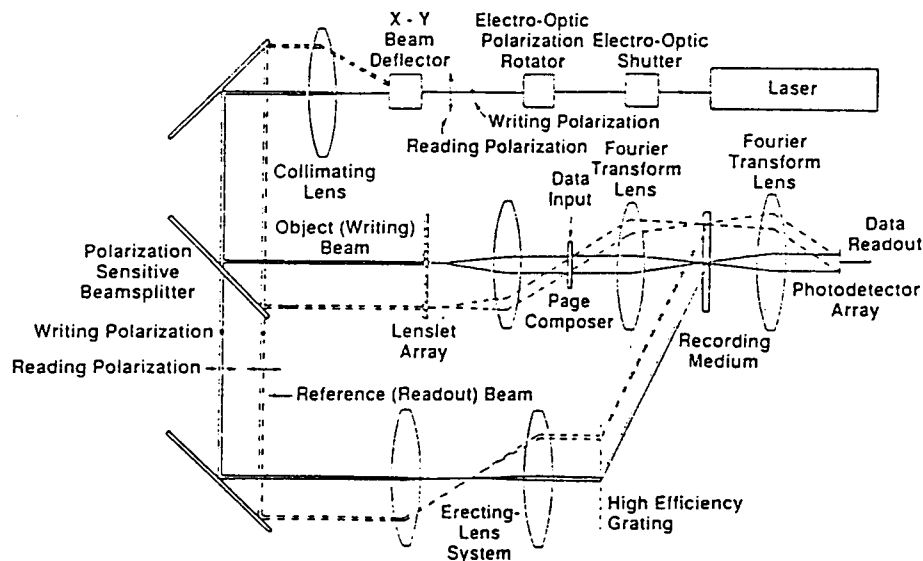


Figure A-1. Holographic data storage system with no moving parts.

The data was recorded as a small Fourier transform hologram at a location on the storage medium determined by a two-dimensional beam deflector. The hologram was created by the interference of light from a uniform "reference" beam and an "object" beam consisting of an array of data points created in an optical component called "page composer" at a fixed location in space. The optics were designed such that the object beams from every deflector position would pass through the page composer, and would be such that the object and reference beams would coincide exactly at every location of the storage medium addressed by the deflector. In this manner, a single, fixed page composer and a single, fixed

photodetector array were used for handling data in the whole memory system, regardless of its capacity. For writing, the data input was placed into the page composer to spatially modulate the object beam, and the recording was made as a hologram using both the modulated object beam and the reference beam. For readout, the object beam was shut off, and the reference beam was deflected toward the selected hologram to interrogate it. The data would be reconstructed as a real image of the page composer at the detector array, as the first-order diffracted light from the hologram.

The memory thus consisted of an array of holograms, each hologram storing the content of the page composer. The elegance of the system stems from its simplicity and its small component count. Only one laser source is used for the whole memory. The page composer and photodetector array are fixed in space. The lenslet array and the lens in front of the page composer ensure that all the object beams pass through the page composer. The lens after the recording medium ensures that the readout forms an image of the page composer at the photodetector array regardless of the hologram location.

Holographic data storage was considered attractive because of its redundancy. Indeed, the loss of part of a small hologram (through scratches, dust, material imperfection) does not result in a loss of data. It only reduces signal-to-noise ratio. However, because of the need to spread the object beam over the data page composer and because of the coherence requirements of holography, only high-power gas lasers could be used as light sources, together with very sensitive storage media, such as photographic and some photorefractive media. Furthermore, the storage medium had to be linear, i.e., the contrast had to be a linear function of light intensity. Indeed, a hologram is a superposition of gratings made from the interference of light of different intensities and directions (the object) with a reference beam. The readout (the reconstruction of the object), obtained by exposing the hologram to the reference beam alone, is simply the first-order diffracted light from those superimposed gratings. Only the first order is significant, either because the grating efficiency is not very large or because the hologram is thick (the readout is at the Bragg angle if the hologram is thick). If the storage medium is not linear with exposure, the strongly exposed regions will be overexposed, and the weakly exposed regions will be underexposed. A sinusoidal intensity pattern will record a square-wave pattern. Upon readout, high-order diffracted light from various Fourier components of the gratings will appear at the same location as the desired readout and will result in a loss of

contrast or an increase of cross-talk noise. With non-linear media such as magneto-optics, a non-holographic version of this concept of page-oriented memory would then be desired.

B. NON-HOLOGRAPHIC, PAGE-ORIENTED MEMORY

Modern optical data storage systems use rewritable media such as magneto-optic (MO) or phase-change media, and use semiconductor laser devices as sources of write and read energy. These media are non-linear, and the coherence length of light from semiconductor laser diodes is not as long as that of gas lasers. For those two reasons, bit-by-bit recording is preferable over holographic recording for those media. Such a system was the first type we investigated in the course of this work, and it is illustrated in Fig. A-2.

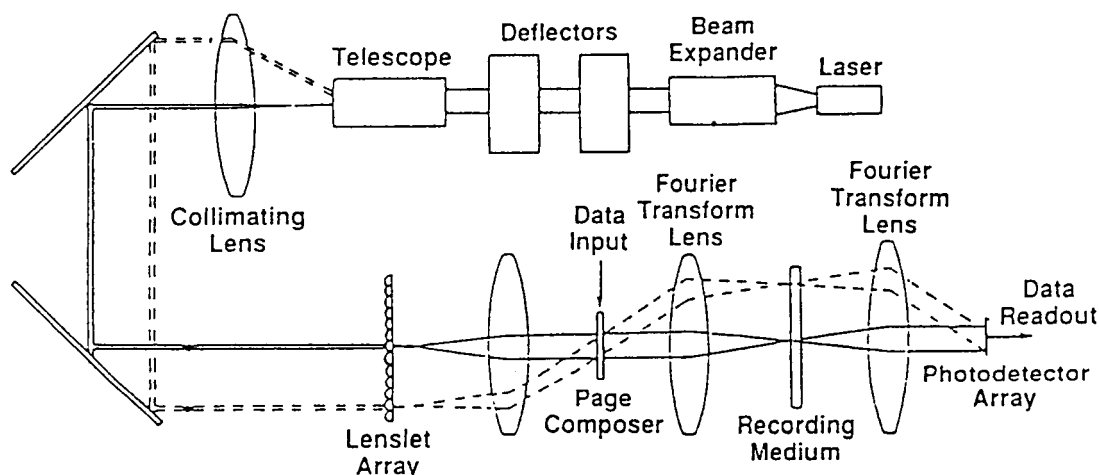


Figure A-2. Non-holographic data storage system having no moving parts.

This system uses the same principle of a laser deflector, fixed page composer, fixed storage medium, and fixed photodetector array. Instead of a hologram, the data array from the page composer is recorded directly on the storage medium. The laser can be a semiconductor phased array source with enough power to record one word of data, and the size of the page composer should have enough switches for setting up one word. For a 10^6 bit module, the

deflector would have 1024 by 32 positions and the page composer would have the size of a 32-bit word.

Our conception of the operation of this memory is as follows: For writing, the word to be recorded is switched into the page (now word) composer, which can be simply a linear array of independent optical switches, and the deflector moves the beam to the selected memory location while passing the light through the word composer. The lenslet array, the collimating lens, and the Fourier transform lenses on both sides of the page composer ensure that the light will pass the word composer for any memory location. Upon readout, the desired memory location is again selected, and all the switches of the word composer opened. The light thus reads the bit pattern stored on the medium, and the Fourier transform lens between storage medium and photodetector array ensures that the readout light falls onto the photodetector array regardless of the selected storage location.

C. DRAWBACK OF PAGE-ORIENTED SYSTEMS

The concept of using a page or word composer designed to create many bits, through which light from all the deflector positions is required to pass, creates the need to place some optical components between the deflectors and the word composer. Also the need to minimize cross-talk at the detectors places constraints on the bit spacing in the page composer. Those constraints cause the physical space utilization system to be unacceptably large for the storage capacity of interest and the packing density to be low. In Appendix B, we show that even for a memory with a modest capacity of 10^6 bits, the space between the center of the laser and the lenslet array in Fig. A-2 is the order of 2.5 m for this page-oriented memory. In Appendix C, we show that the need to place guard spaces between the bits of the word composer and the detector array causes the packing density to be given by

$$P = \left(\frac{NA}{2\sqrt{2\lambda}} \right)^2 \quad (A-1)$$

where NA is the numerical aperture of the imaging lens and λ is the recording light wavelength. On the other hand, the packing density of rotating disk systems is [14]

$$P(\text{rotating disk}) = \frac{NA}{1.2\lambda^2} \quad (\text{A-2})$$

giving

$$\frac{P}{P(\text{rotating disk})} = .14 NA \quad (\text{A-3})$$

Equation (A-3) indicates that for a system with $NA = .5$, the packing density of a page-oriented optical disk without moving parts is only 7% that of a rotating disk system. This analysis has led us to depart from the historical approach and to propose the new designs described in the main text of this report.

Appendix B

SIZE CONSIDERATION FOR A PAGE-ORIENTED OPTICAL MEMORY

A 32-bit word page-oriented memory designed in accordance to Fig. A-2 would have a 32-bit by 32-bit page composer and a 32-position deflector for each coordinate (X and Y). The page composer is a 32 spots by 32 spots matrix of optical switches whose size is much larger than λ in order to avoid significant diffraction spread. The output light beams from the collimating lens are parallel to each other, and their diameter is about the same as the individual elements of the lenslet array located in the collimating lens' focal plane. If the size of the lenslet element is "a," as shown in Fig. B-1, the 32 positions of each deflector require the lens diameter to be $D = 32a\sqrt{2}$. Furthermore, for the beams to remain parallel and collimated with spot size "a," the focal length must be $F = a^2/\lambda$. For $a = 1 \text{ mm}$ and $\lambda = 0.8\mu\text{m}$, this gives $D = 4.5 \text{ mm}$ and $F = 1.25 \text{ m}$, and the distance between the telescope and the lenslet array or 2.5 m ($2F$). This size factor, together with the packing density reduction and the high power for the laser source makes this type of system impractical.

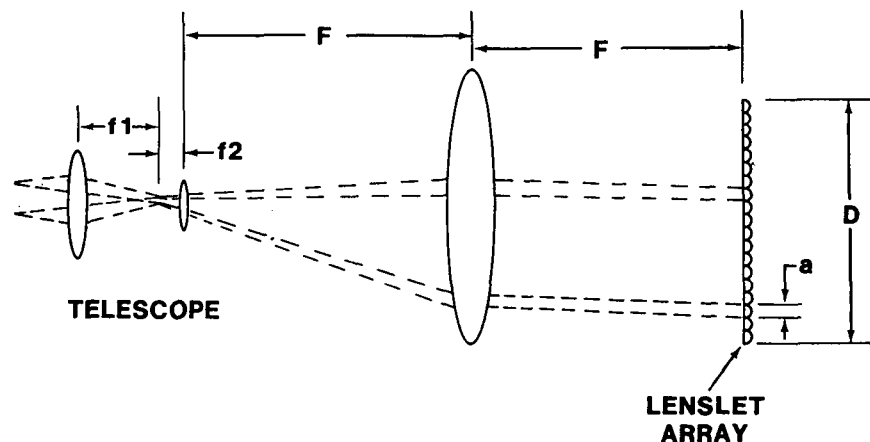


Figure B-1. Optics of deflection system for page-oriented memory.

Appendix C

PACKING DENSITY, MEMORY SIZE, AND CAPACITY

The storage capacity and packing density of an optical data storage can be calculated by considering the geometrical relationships that must be satisfied by the word composer or laser diode array, the lens, the stored data array, and the photodetector [16]. A simplified geometrical arrangement between the various components is shown in Fig. C-1. Let N be the number of bits in a word, d the size of a bit element at the word composer, and c the ratio of center spacing to element size. The light diffracted by the word composer is collected by the lens and focused onto a small region of the storage medium, where it is stored as a word. Let \bar{N} be the number of stored words, \bar{d} the size of a word in the storage medium, and \bar{c} the ratio of the center spacing to physical word length on the storage medium. Following an analysis by A. Vander Lugt [17], the aperature ratio R , which is the ratio of the clear diameter of the lens to the focal length f , is:

$$R = 2(h + \bar{h}) \quad (C-1)$$

where h is the radius at the lens covered by the principal marginal ray (PMR), and \bar{h} is the radius covered by the principal primary ray (PPR) from the word composer. Equation (C1) can be written as:

$$R = \sqrt{2} Ncd/f + \sqrt{2} \bar{N}\bar{c}\bar{d}/f = R_c + R_s \quad (C-2)$$

where $R_c = \sqrt{2} Ncd/f$ can be considered as the aperture ratio of the word composer, and $R_s = \sqrt{2} \bar{N}\bar{c}\bar{d}/f$ is the aperture ratio of the storage medium.

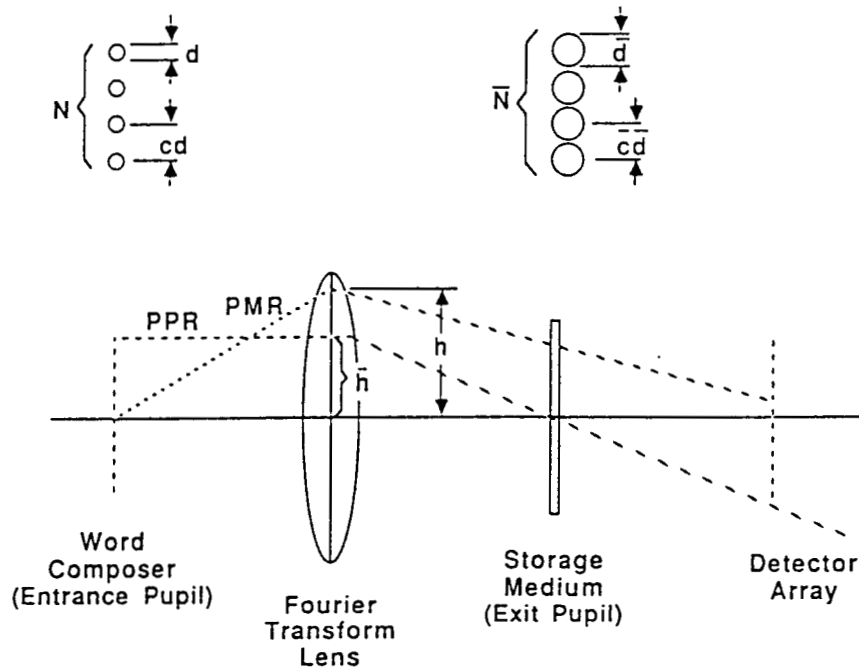


Figure C-1. Simplified geometrical arrangement to evaluate packing density.

The storage capacity is $Q^2 = (N \bar{N})^2$ and, from Eq. (C-2) one obtains

$$Q = (R - \sqrt{2} Ncd/f) \frac{Nf}{\sqrt{2}cd}$$

The maximum storage capacity is obtained by setting $dQ/dN = 0$. This occurs for $R = 2 R_c$, and using the expression

$$\bar{d} = 2\lambda f/cd \quad (C-3)$$

as the relation between the size of the stored word with respect to the bit spacing on the word composer, we find

$$Q_{\max} = \frac{R^2 f}{16c\lambda} \quad (C-4)$$

Equation (C-4) shows that the maximum storage capacity is determined solely by the parameters associated with the lens system. To increase the storage capacity, one must increase the aperture ratio and the focal length of the lens.

The linear packing density is $P_1 = N/\bar{d} = R_c/2\sqrt{2}\lambda$ and the areal packing density P_a is the square of P_1 , or

$$P_a = \left(\frac{R}{4\sqrt{2}\lambda} \right)^2 = \left(\frac{NA}{2\sqrt{2}\lambda} \right)^2 \quad (C-5)$$

Equation (B-5) shows that the maximum packing density is dependent only on the aperture ratio (roughly twice the numerical aperture) and the wavelength of the light.

This analysis has the following implications:

- The storage capacity cannot be made arbitrarily large by increasing the storage area.
- For a given lens system, increasing the number of bits in the word composer or the number of stored locations does not increase the capacity.

Although the design makes optimum use of the storage medium, in the sense that the stored words are next to one another, a comparison of the packing density obtained from this analysis for a page-oriented, non-moving part system, and the packing density of a rotating disk system gives Eq. (A-3), which shows that the packing density for the page-oriented memory is only about 7% of that of an optical disk for $NA = 0.5$. This analysis shows that the designs proposed in the main body of this report are much more attractive than this page-oriented approach.

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